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Scattering of High-Frequency Acoustic Energy from Discrete Scatterers on the Seafloor: Glass Spheres and Shells

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Abstract

Shells and shell debris are common at the water/seafloor interface. Quantifying the scattering from shells is thus important for predicting high frequency backscattering from the seafloor. A backscattering experiment is described in which glass beads (radius equal to 1.75 cm) and shells (largest dimension up to about 10 cm) were placed near a bottom-mounted sonar and backscattering examined as a function of the number of discrete scatterers [Supported by Office of Naval Research – USA]

1. Introduction

In the fall of 1999 a high-frequency acoustics experiment, "SAX99" (for sediment acoustics experiment – 1999) was performed about 2 km from shore on the Florida Panhandle near Fort Walton Beach. As part of that experiment, discrete scatterers (both marbles and shells) were placed on the seafloor in the field of view of the Benthic Acoustic Measurement System (BAMS), a bottom mounted, autonomous, tripod that includes an acoustic transmitter/receiver operating at 40 kHz. The goal was to determine the backscattering strength as a function of the density of discrete scatterers. Models aimed at predicting this scattering strength can then be tested against this experimental data. These experiments were motivated by the suggestion of Richardson and Briggs [1] that scattering and propagation of high-frequency acoustic waves is dominated by the distribution of shells on sandy sediments in the northeastern Gulf of Mexico.

In this paper we first discuss the experimental apparatus and procedure then present the backscattering strengths derived from the measurements as well as the backscattering strengths predicted by a very simple model (Section 2). The details of the model are given in Section 3. The model is only a small step toward the developing a predictive capability for scattering from discrete scatterers but data/model comparison gives guidance as to what effects may need to be considered in more sophisticated models.

2. Experiments

2.1 Apparatus - BAMS

BAMS [2] is a bottom-mounted autonomous system including a tripod frame, scanning hardware to allow a transducer to be rotated in the horizontal plane, and controlling electronics. The 40 kHz transducer used in the results presented here is mounted such that its vertical beamwidth allows scanning of a 30-40 meter radius region of the seafloor centered at the tripod. The horizontal beamwidth is approximately 5 degrees. The transducer sends out a pulse with a range resolution of 0.4 m. The azimuthal resolution is a function of range from the tripod; at 11 meters the azimuthal resolution is about 1 meter. The transducer calibration and tilt measurement resolution imply an uncertainty of about ± 1 dB in the absolute level of mean backscattering if a large ensemble of measurements is used. During SAX99 BAMS acquired data for 29 days. The first 18 days it scanned the seafloor once every 90 minutes. The last 11 days it scanned once every 30 minutes.

2.2 Procedure and Results

Before discrete scatterers were introduced, 2m-x-2m square areas of the seafloor were marked off with plastic tent stakes and nylon twine. Two such areas were set up near BAMS for the discrete scatterer experiments discussed here. Each treatment area was orthogonal to the radial acoustic beams, centred at 11 m from the centre of the BAMS tripod, and separated by 2 m of open seafloor. Exact pixel locations of the 2m-x-2m treatment areas relative to the BAMS co-ordinate system were determined by placing 0.2-m radius liquid filled target spheres directly behind each treatment area. The target spheres provided high target strength markers. After removal of the target spheres the treatment areas were acoustically indistinguishable from the surrounding area suggesting that manipulations by divers or presence of the marking systems had little effect on acoustic backscattering

strength. In one of the areas 0.0175 m radius spheres (marbles) were randomly placed at increasingly dense concentrations, removed, added again, and then buried as given in Table 1 (Fig. 1). Mollusc shells of various sizes and concentrations were placed in the other treatment area (Table 1 and Fig. 1). Underwater stereo photographs indicate that the "large" shells in Table 1 have a mean diameter of about 6 cm while the "small" ones have a mean diameter of about 3 cm. The mollusc shells were never exposed to air during collection or subsequent manipulation.

Treat- ment #	Marble Treatment Area (ref. Fig. 2)	Exp. (dB) +/- 1	M1 (dB)	M2 (dB)	Shell Treatment Area (ref. Fig. 3)	Exp. (dB) +/- 1
1	60 marbles added	-25	-29	-23	81 large shells added – inside of shells up	-27
2	190 marbles added	-21	-23		Shells flipped over – inside of shells down	?
3	250 marbles added	-21	-20		200 small shells added – inside of shells down	-26
4	250 marbles added	-19	-18		All shells removed	-31
5	250 marbles added	-20	-17		All shells added – inside of shells down	-24
6	All marbles removed	-35				
7	61 marbles added	-22	-29	-23		
8	250 marbles added	-22	-22			
9	250 marbles added	-19	-20			
10	marbles buried flush with the sediment surface	-28				
11	marbles buried 2-cm below sediment surface	?				

Table 1: Treatments carried out at two different sites in view of BAMS along with measured backscattering strengths (ref. Figs 2 and 3) as well as model results (M1 and M2 columns) for the marble treatments.

During the time of the experiments 600 scans were carried out by BAMS. Treatments were scheduled to avoid periods when BAMS was transmitting. The transducer resolution allowed 9 values of scattering strength to be calculated in the 2m-x-2m treatment area for each scan. The 9 non-dB values (the scattering coefficients) were averaged and then the mean scattering strengths plotted. The results are shown in Figs. 2 and 3 as a function of time measured as the number of days after 00:00 Oct 22, 1999. The vertical dashed lines in each figure indicate the time of the treatment and are labelled with the treatment number from Table 1.

The scattering coefficients for all the scans between treatments (excluding 5 scans near each treatment time when divers might have been in the field of view) were averaged and the mean scattering strengths resulting from the treatment determined. Those values are given in the experiment columns of Table 1. For cases where the amount of time between treatments was small and the scattering strength highly variable no value is given. It is important to note that all treatments result in scattering strengths much larger than that of the natural seafloor (the first part of each of the figures indicates that without discrete scatterers the scattering strength is about -35 dB). The density of shells for treatment 1 is only about 20 per m² of the seafloor, not unrealistic in many natural environments.

Of particular note for the treatments is what seems to be a saturation effect, i.e., though marbles are added for each of treatments 2 through 5 and in 7 through 9 the scattering strength does not increase significantly.

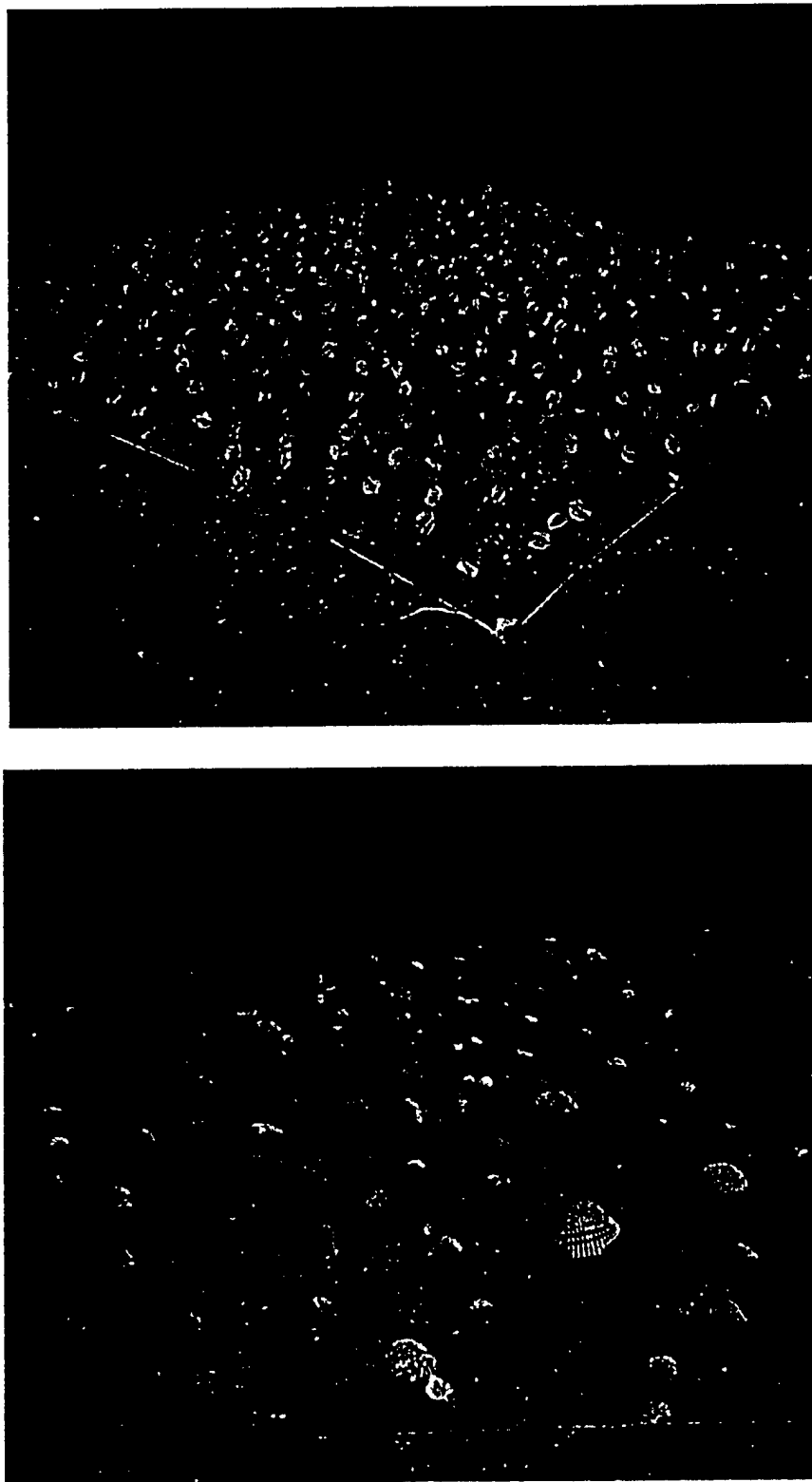


Figure 1 The top photograph shows a marble treatment and the bottom shows a shell treatment

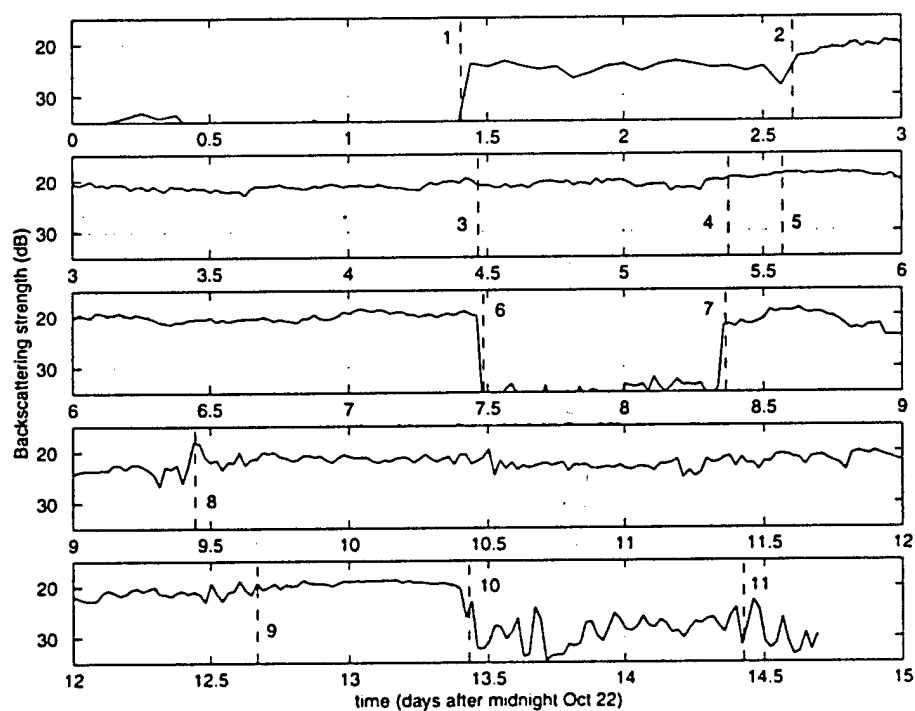


Figure 2 Backscattering strength measured in the region of the seafloor where marble treatments were performed. Time is measured relative to 00:00 Oct 22 (labeled midnight Oct 22 in figure).

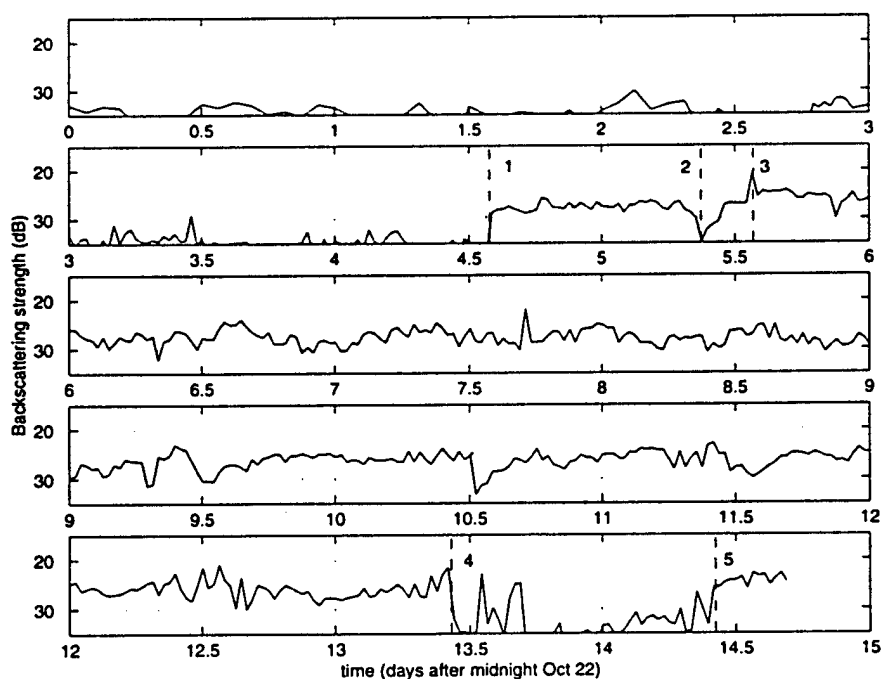


Figure 3 Backscattering strength measured in the region of the seafloor where shell treatments were performed. Time is measured relative to 00:00 Oct 22 (labeled midnight Oct 22 in figure).

The marble treatments were not meant to mimic natural conditions but to help in initial model development. It was hoped that success (and failure) in modelling the marble scattering results would lend insight into at least some of the physics of scattering from natural discrete scatterers as such as shells. The next section outlines a simple scattering model for the marbles, from which the values labelled M1 in Table 1 were derived. The same basic model with an addition to account for the water/sand interface leads to the values labelled M2 in Table 1.

3. Simple Target Strength Based Model

The general philosophy of the model discussed here is similar, in many respects, to that of Stanton [3]. However, the Lambert's law grazing angle dependence he includes is not incorporated into the model since, though Lambert's law approximates the empirical grazing angle dependence seen for some surfaces, there is no reason to believe it should hold for the discrete scatter situation being examined.

The model, in its simplest form, ignores scattering from the sediment surface, which is justified here because of the much lower seafloor scattering strengths measured before marble treatments (Fig. 2). The model simply adds up the target strengths of each marble in a 1-m² area assuming that marbles scatter like rigid spheres in free space and that the ka (k is $2\pi/\text{acoustic wavelength}$ and a is the marble radius) of the marbles is sufficient that the geometric cross section can be used in deriving a target strength for individual marbles. This assumption is valid for the acoustic frequency and marble size used ($ka=2.9$) used in this experiment [3]. According to [4] the scattering strength is therefore

$$SS = 20 \cdot \log_{10} \left(\frac{Na}{2} \right) \quad (1)$$

where N is the number of marbles per m² on the seafloor. Remembering that the marble treatments were over a 4-m² area of the seafloor gives the values given in column M1 of Table 1. Comparison of the experiment and M1 values indicate that, though in several cases the values are within a couple of dB, the effects of saturation discussed above are not captured in the model. Furthermore, treatments 1 and 7, that have the least number of marbles have the largest difference between experiment and model. Three obvious effects not accounted for are; the elasticity of the spheres, the presence of the boundary, and multiple scattering as the spheres get closer.

It is only a small complication to generalise (1) somewhat to include the elastic effects of spheres via the addition of a factor f , called the form function [5] that is a function of ka

$$ss = 20 \log_{10} \left(\frac{Na}{2} \right) + 20 \log_{10} (|f(ka)|) \quad (2)$$

For an elastic sphere in free space a main contributor to f is the specular reflection from the front of the sphere [5] giving

$$f(ka) = R(90) \cdot \exp(-ika) \quad (3)$$

where R is the reflection coefficient at normal incidence for a water/glass interface. The phase term is relative to a ray traveling in water to and from a reference point corresponding to the spheres center.

The effects of a sphere sitting on the water/sand interface can also be incorporated into f if the interface is assumed to be flat and geometrical acoustics is used. For a sphere placed on the interface there are four backscatter paths as shown in Fig. 3.

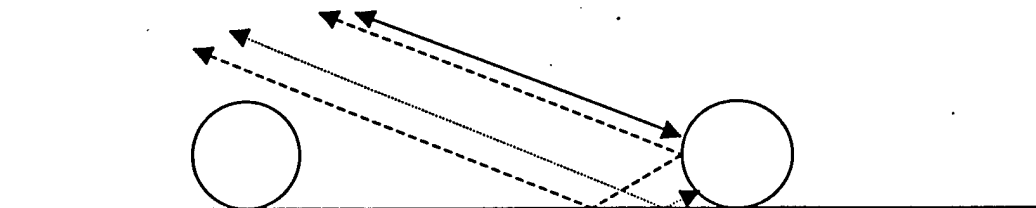


Figure 3 Four backscatter acoustic paths for a sphere on a flat interface. The solid line is the free space path giving (3), the dashed line represents two symmetric paths that either scatter from the sphere first or the interface first, the dotted line is a path that scatters from the sphere once and the interface twice.

Using this picture f can be written

$$f(ka) = R(90) \cdot \exp(-i2ka) + 2 \cdot R(90 - \theta_i) \cdot \Gamma(\theta_i) \cdot \exp \left[ika \left(-\cos(\theta_i) + \frac{2}{\sin(\theta_i)} - [1 + 2 \cot(\theta_i)] \cos(\theta_i) \right) \right] + R(90) \cdot \Gamma^2(\theta_i) \cdot \exp \left(ika \left[\frac{4}{\sin(\theta_i)} - 4 \cot(\theta_i) - 2 \right] \right) \quad (4)$$

where Γ is the reflection coefficient for the sand/water interface and θ_i is the incident grazing angle.

Using an incident grazing angle of 16° , a water speed of 1531 m/s, a sediment sound speed of 1775 m/s, a glass longitudinal wave speed of 5100 m/s, a glass shear wave speed of 2840 m/s, a water density of 1000 kg/m³, a sand density of 1970 kg/m³, and a glass density of 2240 kg/m³ in (2) with f given by (4) gives -20 dB for treatments 1 and 7. This is somewhat high but closer than when the free space, rigid sphere model was used. Finally, underwater photographs indicate that marbles were often buried to about one quarter of their radius. This motivates eliminating the last term in (4) that corresponds to the path in Fig 3 that scatters from the lowest point of the sphere. The result obtained is given as M2 in Table 1. This value (perhaps fortuitously) is close to that obtained in the experiments.

Examining other treatments using this approach may not be particularly fruitful because the effects of multiple scattering can become significant, as can be seen by examining Fig. 3. For the case of 62 marbles per m² (the density after treatment 2) the mean separation between marbles is small enough that, for a 16° incident grazing angle and 0.0175 m radius spheres, the dashed paths in Fig. 3 for one sphere could be shadowed by another sphere. This is the beginning of multiple scattering effects that we conjecture would lead to the saturation effect seen in the data and discussed earlier.

4. Conclusion

The modelling effort carried out to date for the marbles, though simple, indicates that interface and multiple scattering effects may be important in understanding the experimental results. The experimental results stand on their own as useful for testing more sophisticated models. More importantly, the experimental results demonstrate the potential importance of the discrete scatterers in backscattering situations, and thus the need for further effort in this area.

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